

Solutions

1. Astronomers find that 90% of the stars observed in the sky are on the main sequence of an H-R diagram; why does this make sense? Why are there far fewer stars in the giant and supergiant region?

Being on the main sequence means that the star is converting hydrogen to helium in the core. Since stars are made mostly of hydrogen, this process takes approximately 90% of a star's life. Thus it makes sense that the 90% of the stars observed at some particular time would be undergoing this process. Being a red giant star is a brief stage in the life of each star, when the star is readjusting to the loss of energy from the fusion of hydrogen. In a relatively short time (in the timescale of stars), the core collapses until it is hot enough for the fusion of helium into carbon, restoring the star's equilibrium. Since this is only a brief stage in the life of the star (taking only a few percent of the star's life), it makes sense that only a few percent of stars will be found in the giant stage at any given time.

2. Describe the evolution of a star with a mass similar to that of the Sun, from the protostar stage to the time it first becomes a red giant. Give the description in words and then sketch the evolution on an H-R diagram.

During the protostar stage, gravity gathers gas and dust toward a central location, which increases in temperature and pressure. Eventually, the temperature and pressure at the center of the gas and dust will reach critical thresholds and the nuclear fusion of hydrogen into helium will begin in what is now called the core. When this happens, the protostar officially becomes a zero-age main sequence star. For the next 10 billion years or so, the star will stably undergo nuclear fusion as it remains on the main sequence. Once the hydrogen gas runs out in the core, gravity will begin to re-collapse the stellar atmosphere above the core, which in turn increases the temperature and pressure within the core again. While this occurs, a hydrogen shell around the core will begin nuclear fusion, causing the star to swell and become more luminous as it enters the red giant phase. Eventually, the temperature and pressure in the core will reach another set of critical thresholds and the nuclear fusion of helium into carbon will commence in an explosive helium flash, officially beginning a more stable phase.

3. Describe the evolution of a star with a mass similar to that of the Sun, from just after it first becomes a red giant to the time it exhausts the last type of fuel its core is capable of fusing.

During the red giant phase, the star is swelling up (becoming larger and cooler at the surface) due to the fusion of hydrogen in a shell around the collapsing core. Eventually, the helium gets hot enough to be fused to carbon in the core, and the star regains a temporary equilibrium. When all the helium hot enough to fuse carbon is exhausted in the core, the star swells again as the inert core of carbon tries to reach a temperature and pressure necessary for the next fusion stage. For stars like the Sun, that is not possible after the fusion of helium into carbon (and a bit of oxygen), so this is the last fuel it is capable of using.

4. A star is often described as "moving" on an H-R diagram; why is this description used and what is actually happening with the star?

What is actually happening is that the star is progressing into different evolutionary stages, during which various properties of the star (mass, luminosity, radius, etc.)

change. The H-R diagram plots a star's luminosity versus its surface temperature. As the star evolves, these characteristics change. When the star is plotted on an H-R diagram as it goes through these evolutionary stages, the star's "dot" on the diagram moves from one location to another.

5. Certain stars, like Betelgeuse, have a lower surface temperature than the Sun and yet are more luminous. How do these stars produce so much more energy than the Sun?

Certain stars, like Betelgeuse, have swelled up to be giant stars. They produce more overall energy because of their much larger size (while each piece of the star's surface is cool, there are so many pieces that, overall, the stars give out more energy).

6. Gravity always tries to collapse the mass of a star toward its center. What mechanism can oppose this gravitational collapse for a star? During what stages of a star's life would there be a "balance" between them?

Outward radiation pressure from gamma rays created by fusion in the core of the star opposes the inward gravitational collapse when a star is in equilibrium. Balances are generally achieved when there is a "fuel" (element) hot enough to fuse in the core, like during the main-sequence stage when hydrogen fusion occurs and during helium core fusion after the helium flash.

7. Why are star clusters so useful for astronomers who want to study the evolution of stars?

It is reasonable to assume that the individual stars in a cluster all formed at nearly the same time from the same cloud of gas and dust. As a result, the only initial difference between the stars is their mass (and not their composition or the time that they began). Therefore, as we put all the stars in a cluster on an H-R diagram, we can see how stars of different mass will change their positions in the diagram over time and build up a picture of how stars of different mass go through the stages of their lives. Also, because high-mass stars evolve much more quickly than low mass stars, we can estimate the age of a cluster of stars by observing where its stars are currently leaving the main sequence.

8. Would the Sun more likely have been a member of a globular cluster or open cluster in the past?

The Sun more likely would have been a member of an open cluster with other stars that would have formed from the same cloud of gas and dust. Stars in an open cluster can have a range of ages, whereas stars in a globular cluster are all very old—much older than the current age of the Sun. Also, if we had been born in a crowded (dense) globular cluster, all the stars in the cluster would still be around us and with us. In contrast, stars in a loose open cluster can disperse with time, leaving a star like the Sun alone later in its life (just as we now are).

9. Suppose you were handed two H-R diagrams for two different clusters: diagram A has a majority of its stars plotted on the upper left part of the main sequence with the rest of the stars off the main sequence; and diagram B has a majority of its stars plotted on the lower right part of the main sequence with the rest of the stars off the main sequence. Which diagram would be for the older cluster? Why?

The crucial idea here is that the more massive the star, the more quickly it goes through each stage of its life. The older cluster would be represented by diagram B, which indicates that higher-mass stars have already evolved past the main-sequence stage of their lives, while the lower-mass stars continue to be on the main sequence. Diagram A indicates a young cluster, as only the higher-mass stars have reached the main-sequence stage and the lower mass stars are still protostars and have yet to reach zero-age main sequence.



10. The nuclear process for fusing helium into carbon is often called the “triple-alpha process.” Why is it called as such, and why must it occur at a much higher temperature than the nuclear process for fusing hydrogen into helium?

A helium nucleus (two protons and two neutrons) is called an alpha particle by physicists, and it takes three (triple) helium nuclei to simultaneously come together to ultimately form a carbon nucleus. Since each helium nucleus has two positive protons, the six protons repel each other, and it takes a lot of kinetic energy and temperature to get the three helium nuclei to stick together.

11. Pictures of various planetary nebulae show a variety of shapes, but astronomers believe a majority of planetary nebulae have the same basic shape. How can this paradox be explained?

There is a variety of planetary nebula shapes because astronomers are looking at the same basic shape (a thicker torus right around the star or stars and outflows through the hole in the torus in opposite directions) from different points of view.

12. Describe the two “recycling” mechanisms that are associated with stars (one during each star’s life and the other connecting generations of stars).

One recycling mechanism is that stars can sometimes use the “ash” from one nuclear fusion process as the “fuel” for the next (i.e., hydrogen fuses into helium, and then helium fuses into carbon). Another recycling mechanism is how all stars eventually end their lives by sending back into the cosmos a considerable part of their mass and all the elements within; this material becomes part of the interstellar medium of gas and dust that can form more stars.

13. In which of these star groups would you mostly likely find the least heavy-element abundance for the stars within them: open clusters, globular clusters, or associations?

Globular clusters: they have very low heavy-element abundances because they contain very old, first-generation stars that are composed of only hydrogen, helium, and traces of lithium.

14. Explain how an H-R diagram of the stars in a cluster can be used to determine the age of the cluster.

Initially, most of the stars in a cluster will be distributed all along the main sequence of the H-R diagram. Eventually, the more massive stars will end the hydrogen fusion in the core and move off the main sequence, creating a “turn” in the distribution of the stars in the cluster on the H-R diagram. As more time goes by, stars of even lower mass (and lower on the main sequence) will move toward the giant branch of the diagram, leaving the top of the main sequence without stars on it. The location of the turn thus indicates the age of the cluster.

15. Where did the carbon atoms in the trunk of a tree on your college campus come from originally? Where did the neon in the fabled “neon lights of Broadway” come from originally?

The carbon could have come from the product of helium fusion (the triple-alpha process) in a high-mass star. Neon must have come from fusion inside of a high-mass star, as its atomic number is higher than that of carbon and therefore could not be produced in low-mass stars.]

16. What is a planetary nebula? Will we have one around the Sun?

A planetary nebula is the distended outer atmosphere of a giant star as it floats away and is made to glow by ultraviolet light from the hot star that is collapsing inside the nebula. This is a stage that low-mass stars go through. The Sun, which is considered a low-mass star, will eventually have a planetary nebula form around it billions years from now, after it has been a red giant.

17. Would you expect to find an earthlike planet (with a solid surface) around a very low-mass star that formed right at the beginning of a globular cluster’s life? Explain.

The first generation of stars contained only hydrogen and helium and no heavy elements, since there had not been time to fuse them. Globular clusters are very old, so any stars that formed right at the beginning of their lives would be very close to



the first generation of stars in the Galaxy. Since earthlike planets require the presence of heavier elements, we would not expect to find them around such a star.



18. In the H-R diagrams for some young clusters, stars of both very low and very high luminosity are off to the right of the main sequence, whereas those of intermediate luminosity are on the main sequence. Can you offer an explanation for that? Sketch an H-R diagram for such a cluster.

The most massive stars go through each stage of their lives most quickly, while the lowest-mass stars do everything more slowly. In a cluster in which both the most and least luminous stars lie to the right of the main sequence, the most massive stars have already converted the hydrogen in the core to helium and are beginning to evolve to the supergiant stage. The lowest-mass stars have yet to arrive on the main sequence and begin hydrogen fusion; they are still contracting (and moving toward the main sequence as a consequence).

19. If all the stars in a cluster have nearly the same age, why are clusters useful in studying evolutionary effects (different stages in the lives of stars)?

The stars in a cluster presumably have the same age and chemical composition, but they do have different masses. The timescale for the evolutionary process depends critically on a star's mass, with stars of larger mass going through each stage more quickly. In a cluster with many stars, there is likely to be a good distribution of masses and so we can see stars in a variety of life stages. Even clusters of stars with only slightly different masses can vary considerably in their evolutionary stages. Thus, even stars in a rather small mass range can still be at different points in an evolutionary track. These tracks can be compared with theoretical ones from our mathematical models of how stars age.

20. Suppose a star cluster were at such a large distance that it appeared as an unresolved spot of light through the telescope. What would you expect the overall color of the spot to be if it were the image of the cluster immediately after it was formed? How would the color differ after 10^{10} years? Why?

Just after the cluster formed, it would look blue since the light from the cluster would be dominated by the O and B stars. After 10^{10} years, the O and B stars would have died and other main-sequence stars (of about 1 solar mass) would be evolving to red giants. These red giants would be the most luminous stars, so the cluster would appear noticeably red.

21. Stars that have masses approximately 0.8 times the mass of the Sun take about 18 billion years to turn into red giants. How does this compare to the current age of the universe? Would you expect to find a globular cluster with a main-sequence turnoff for stars of 0.8 solar mass or less? Why or why not?

This is older than the age of the universe, which is approximately 14 billion years old. Thus, we would not expect to find globular clusters with main-sequence turnoffs for stars of this solar mass (at least not yet).

